# TECHNICAL NOTES

## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 707

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## COMPRESSION-IGNITION ENGINE PERFORMANCE WITH

## UNDOPED AND DOPED FUEL OILS AND ALCOHOL MIXTURES

By Charles S. Moore and Hampton H. Foster
Langley Memorial Aeronautical Laboratory

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SUMMARY

Several fuel oils, doped fuel oils, and mixtures of
alcohol and fuel oil were tested in a high-speed, single-
cylinder, compression-ignition engine to determine power
output, fuel consumption, and ignition and combustion
characteristics.

Fuel oils or doped fuel oils of high cetane number
had shorter ignition lags, lower rates of pressure rise,
and gave smoother engine operation than fuel oils or doped
fuel oils of low cetane number. Higher engine rotative
speeds and boost pressures resulted in smoother engine op-
eration and permitted the use of fuel oils of relatively
low cetane number. Although the addition of a dope to a
fuel oil decreased the ignition lag and the rate of pres-
sure rise, the ensuing rate of combustion was somewhat
slower than for the undoped fuel oil so that the effective-
ness of combustion was practically unchanged.

Alcohol used as an auxiliary fuel, either as a mixture
or by separate injection, increased the rates of pressure
rise and induced roughness. In general, the power output
decreased as the proportion of alcohol increased and, be-
low maximum power, varied with the heating value of the
total fuel charge.

INTRODUCTION

Most published experimental investigations of fuels
for compression-ignition engines have been principally
concerned with ignition characteristics while engine power
and economy were given but slight consideration (references
1, 2, 3, and 4). In order to improve the ignitibility of
fuel oils, various compounds have been added for the spe-
cific purpose of reducing the ignition lag (reference 5).

The possibility has been suggested that fuel dopes might be added or superior fuels obtained which will enable a greater part of the fuel charge to be burned during the early part of the expansion stroke. French reports (references 6 and 7) indicate that the use of ethyl alcohol as an auxiliary fuel appreciably improved the engine power and the ignition characteristics and decreased the rate of pressure rise and the maximum cylinder pressure.

The purpose of the work presented in this report was to determine the ignition, the combustion, and the engine-performance characteristics of several fuel oils, to determine the effect of adding fuel dopes, and to test the value of alcohol and gasoline as auxiliary fuels. The results have been accumulated from tests of new fuels as they became available. Some of the fuel dopes submitted by private investigators were considered to be ignition and combustion accelerators. Many of the fuels were examined by the U.S. Naval Engineering Experiment Station at Annapolis, Md., to determine their physical-chemical properties and, especially, their cetane numbers. The engine tests reported herein were made by the N.A.C.A. during 1936, 1937, and 1938.

## FUELS

The fuels tested are readily classified into three distinct groups:

1. Fuel oils.

2. Doped fuel oils.

3. Auxiliary fuels.

Table I shows the properties of the fuels of groups 1 and 2 as determined by the Naval Engineering Experiment Station. For the determination of the cetane number, the constant-ignition-lag method and the modified magnetic pick-up method (references 1 and 2) were used on a compression-ignition conversion unit of the C.F.R. engine with the turbulent-type combustion chamber.

Fuel oils.- Fuel 1 is the laboratory fuel oil used by the N.A.C.A. for routine engine tests. It is a distillate from a Pennsylvania or equivalent crude oil. (This fuel is similar to fuel 2 of reference 8.)

Fuel 2 is U.S. Navy M-306, specified for aircraft compression-ignition engines.

Fuel 3 is a commercial marine fuel oil sold on the Atlantic seaboard of the United States.

Fuel 4 is U.S. Navy 7-0-2C, specified for general use in submarines and small boats.

Fuel 5 is No. 3 furnace oil purchased for boiler heating.

Doped fuel oils.- Fuel 6 was obtained by adding 1 percent of ethyl nitrate to the No. 3 furnace oil.

Fuel 7 was obtained by adding 2.5 percent of iso-amyl nitrate to the laboratory fuel oil (i.e., to fuel 1).

Fuel 8 (properties not given in table) was obtained by adding 4 percent of tetranitromethane to the laboratory fuel oil.

Auxiliary fuels.- Fuel 9 (see table I) was a mixture of laboratory fuel oil and 25 percent by volume of 87 octane gasoline (U.S. Army Specification No. 2-92, Grade 87).

Fuel 10 (properties not given in table) was laboratory fuel oil and commercial ethyl alcohol of 92 percent purity by weight. Alcohol was used in proportions of 10, 25, 40, and 80 percent by volume of the total fuel charge when the total charge was mixed by constant agitation and injected from a single valve. When the main and the auxiliary fuels were injected separately from two valves, equal weights of alcohol and fuel oil were used. Recent information had indicated this proportion to be the best from considerations of power.

## FUEL-INJECTION SYSTEMS

For the fuel oils, the doped fuel oils, and the gasoline-fuel oil mixture, only one fuel-injection pump and one valve were used. The pump was cam operated and had a constant plunger displacement with constant start and variable cut-off of injection. Figure 1 shows the arrangement of the fuel-spray axes and the combustion chamber used. For a fuel quantity of 0.00035 pound per cycle in-

jected at 2,000 r.p.m. engine speed, the injection period
was 22 crank degrees as determined by observations with a
stroborama, a stroboscope of the electrical-discharge type.

This fuel-injection system was also used when the al-
cohol and the fuel oil were mixed before injection.  Owing
to immiscibility of the alcohol and the fuel oil, constant
agitation by a small high-speed gear pump was required to
maintain a uniform mixture in the fuel tank.  The uniform-
ity of the mixture injected into the engine was checked by
catching samples of the mixture in a bottle as it was in-
jected by the fuel valve into the air.  The specific grav-
ity of the samples indicated that the mixture was within
±1 percent of the desired proportions.

For the engine tests in which the alcohol and the fuel
oil were separately injected, two separate fuel-injection
pumps and valves were used; each pump had an independent
timing device.  Figure 2 shows the arrangement of the axes
of the two fuel sprays.  The arrangement of the alcohol
spray was chosen to give a reasonably uniform distribution
throughout the combustion chamber without consideration of
the interference of the fuel-oil and the alcohol sprays.

### TEST ENGINE AND TESTS

The displacer-piston combustion chamber and the fuel-
oil spray arrangement used in those tests (see fig. 1)
have been completely described in references 9 and 10.
The more important parts of the test unit and standard
test conditions were as follows:

Engine..................... Single-cylinder, 4-stroke-
                            cycle, 5-inch bore by 7-
                            inch stroke, (137.5 cu. in.
                            displacement).

Engine speed.............. 2,000 r.p.m.

Compression ratio......... 14.5.

Valve timing.............. Inlet opens    27° B.T.C.
                           Inlet closes   28° A.B.C.
                           Exhaust opens  66° B.B.C.
                           Exhaust closes 41° A.T.C.

Operating temperatures... Water (out), 170° F.;
lubricating oil (out), 165° F.

Fuel-injection valves.... N.A.C.A. automatic, spring-
loaded to 3,500 pounds per
square inch opening pres-
sure.

Full-load fuel quantity.. Fuel-air ratio = 0.069.

Power measurement and
absorption............. Electric dynamometer unit.

Air- and fuel-consumption
measurements.......... Gasometer with synchronized
electrically operated stop
watches and revolution
counters.

Indicator................ Modified Farnboro for indi-
cator cards.

Maximum cylinder-pressure
measurement........... Trapped-pressure valve and
pressure gage; indicator
card for balanced pres-
sures.

For each fuel oil, doped fuel, or auxiliary fuel, en-
gine-performance tests were made at 2,000 r.p.m. for vari-
ous fuel quantities to determine the power and the fuel
consumption. The maximum cylinder pressure, the ignition
lag, and the rate of pressure rise were determined from in-
dicator cards. The injection advance angle was held con-
stant at 12.0° before top center for the determination of
ignition lag at 2,000 r.p.m. With a 5- by 6-inch cyl-
inder and other equipment as before, supplementary tests
were made with a fuel of low cotane number (furnace oil)
at engine speeds from 1,000 to 2,400 r.p.m. and for boost
pressures from 0 to 20 inches of mercury at 2,000 r.p.m.

Indicator cards for the laboratory fuel, the labora-
tory fuel plus 2.5 percent iso-amyl nitrate, the No. 3
furnace oil, and the No. 3 furnace oil plus 1 percent
ethyl nitrate were analyzed to determine the total amounts
of effective fuel burned during various crank angles of the
expansion stroke. By "effective fuel burned" is meant the
combustion of the quantity of fuel required to produce the

change in enthalpy (total heat) recorded on the indicator
diagrams; the term does not include the fuel dissipated as
heat losses.

## RESULTS AND DISCUSSION

### Fuel Oils

The indicator card of figure 3 is typical for the un-
doped fuel oils (group 1) used in each particular test.
The card shows not only the pressure-time record for the
standard injection advance angle but also the retarded-in-
jection record required to determine the break-away from
the compression line at the start of burning. Figure 3
can be considered a reference card because the fuel was
the standard laboratory fuel oil and has a reasonably high
cetane number, 62. The break-away on all of the cards is
a gradual change in slope except for No. 3 furnace oil (fig.
4). For the No. 3 furnace oil, the break-away is much more
abrupt. All of the cards in this group except that for the
furnace oil show two distinct rates of pressure rise. The
first rate (and the only rate for the furnace oil) is at-
tributed to the rapid burning of the fuel accumulated dur-
ing the ignition lag. The second, slower rate occurs up
to the time of cut-off of injection. On the indicator
card for No. 3 furnace oil, a definite reduction in com-
pression pressure occurs at top center, owing to the fuel
vaporization and the cooling of the air charge.

The different combustion characteristics of the sev-
eral fuels are shown in table II, which gives detailed nu-
merical results obtained from an analysis of the indicator
cards. For constant injection advance angles, the ignition
lag decreased with increasing cetane number by as much as
50 percent. The maximum ignition lag, 12.5°, was for the
No. 3 furnace oil having a cetane number of 29.9, and the
minimum lag, 8.0°, was for the commercial marine fuel oil
having a cetane number of 58.0. Injection of the labora-
tory or the commercial marine fuel oil could be retarded to
12° after top center before misfiring occurred; injection
of the furnace oil, however, could be retarded only to top
center. Rates of pressure rise follow very nearly the var-
iations of ignition lag; i.e., longer lags cause higher
rates of pressure rise owing to greater accumulations of
fuel at the time of ignition. Although the maximum cylin-
der pressure did not change greatly, the highest value

occurred with the fuel of lowest cetane number (No. 3 furnace oil), as did the roughest running and the harshest combustion sound. Ignition lag, then, is the factor controlling rates of pressure rise, maximum cylinder pressure, and combustion sound for a given rate of injection.

No engine-performance curves are presented for the several fuel oils because the mean effective pressures and the fuel consumptions were the same for each fuel. The mean effective pressures and the fuel consumptions shown later (fig. 10) for undoped laboratory fuel oil are typical of each of the fuel oils being discussed. The various fuel oils with the same injection advance angles but with different ignition lags gave identical power outputs and fuel consumptions within the limits of experimental accuracy. Fuel oils of low cetane number, however, gave higher balanced cylinder pressures than fuel oils of high cetane number. Table I shows that the maximum difference in heating values of the fuel-oil group is 3 percent, No. 3 furnace oil having the lowest and laboratory fuel oil having the highest values. The low heating value, however, did not reduce the power because more of the fuel burned in the early part of the expansion stroke (as will be seen later) to give a more effective combustion cycle. The differences in the exhaust conditions were negligible for all the fuel oils. It is certain that, of the fuel oils tested, the fuel of highest cetane number did not give a higher mean effective pressure or a lower fuel consumption but did give smoother engine operation.

Engine operation with the No. 3 furnace oil being too rough to be acceptable, tests were made with a 5-inch by 6-inch cylinder under conditions intended to make the operation smoother. It was believed that the rate of pressure rise per degree and the roughness could be reduced by increasing the engine speed. As the engine speed was increased from 1,000 to 2,400 r.p.m. (fig. 5), the angular rate of pressure rise tended to decrease and the extreme roughness decreased to a slight roughness. Increasing the engine speed not only increases the angular velocity but also increases forced air-flow velocity in the combustion chamber. It is this increase in mixing air-flow velocity that decreases the ignition lag and increases the absolute rate of pressure rise. In a combustion chamber that uses forced air flow to mix the fuel and the air, the increased angular and air-flow velocities work against each other as the engine speed is increased; higher air-flow velocities

tend to cause faster fuel mixing and burning and greater
absolute rates of pressure rise, while the higher angular
velocity causes a lower rate of pressure rise per degree.
In a quiescent type of combustion chamber, the effect of
the higher angular velocity should predominate causing the
rate of pressure rise per degree to decrease as the engine
speed increases.

The results of previous tests (reference 10) have
shown that smoother engine operation resulted from increased
inlet-air pressure because the ignition lag and the rate
of pressure rise were decreased. The decrease in ignition
lag is caused by the increased heat per unit volume and the
greater rate of heat transfer rather than by the higher
temperature of the compressed air.

Tests made at full-load fuel quantity with the No. 3
furnace oil over a range of boost pressures to 20 inches of
mercury gave the results shown in figure 6; i.e., the en-
gine operation changed from very rough to slightly rough.
As was expected, the ignition lag and the rate of pressure
rise decreased although, at boost pressures greater than
10 inches of mercury, the rate of pressure rise slightly
increased, possibly because of too much injection advance,
as borne out by the relatively high (reference 10) ratio
of explosion pressure to compression pressure. In general,
the results indicate that higher engine rotative speeds
and boost pressures improve smoothness of engine operation
and permit the use of fuel oils of relatively low cetane
number.

The rates of pressure rise shown in figures 5 and 6
are unusually high. Such values are generally associated
with loud knock and extremely rough engine operation. As
noted on the figures, roughness was encountered but not
destructive conditions.

The decrease in roughness at the higher speeds, despite
the higher absolute rates of pressure rise shown, may be
accounted for by the fact that there is considerably less
acceleration of the pressure-rise rate and that the duration
of the peak pressure is shorter.


### Doped Fuel Oils

The indicator cards shown in figures 7, 8, and 9 were
obtained for the doped fuel oils. Apparently the addition

of dope caused the break-away to become more gradual and smooth. (See figs. 4 and 7.) When the break-away occurred very early, as with the doped laboratory fuel (fig. 9), the pressure rise was practically an extension of the compression curve so that the pressure-rise curve and the compression curve had a common slope. It is also worthy of note that the retarded-injection cards indicate more of a tendency to constant-pressure combustion when dope is added.

Table II includes the ignition and the combustion qualities of the doped fuel oils. The addition of 1 percent of ethyl nitrate to the No. 3 furnace oil increased the cetane number from 29.9 to 47.7. The ignition lag and the rate of pressure rise decreased 13 and 23 percent, respectively; the resulting operation was quite satisfactory. The ignition qualities of the laboratory fuel oil were good even without the addition of a dope. The addition of 2.5 percent of iso-amyl nitrate to the laboratory fuel oil increased the cetane number from 62.5 to 88.1. The ignition lag and the rate of pressure rise were decreased 23.5 and 46.5 percent, respectively. The smoothness of operation was further improved and the break-away became very gradual (fig. 8). One dope of unknown composition that was submitted for test by a private investigator had practically no effect on the ignition qualities or on the engine performance when added to the laboratory fuel oil in proportions of 1 and 2 percent. Another private investigator submitted tetranitromethane as a fuel-oil dope; a 4-percent addition to the laboratory fuel oil decreased the ignition lag and the rate of pressure rise by 23 and 35 percent, respectively.

Of the four fuel dopes tested, three failed to influence either the mean effective pressure or the fuel consumption. That is, although the added dope produced earlier ignition, it apparently produced neither earlier nor more complete combustion of the fuel charge. The addition of 4 percent of tetranitromethane, however, improved the brake mean effective pressure and the corresponding fuel consumption 3 percent. (See fig. 10.) The addition of 1 or 2 percent of the dope had practically no effect. The increase in maximum cylinder pressure of about 25 pounds per square inch for the doped fuel was insufficient to cause the difference shown in performance. The investigator who submitted the tetranitromethane stated that the addition of 4 percent would be too expensive to be commercially practicable.

## Comparison of Ignition Characteristics

Figure 11 gives a summary of the data on ignition lag and rate of pressure rise from table II plotted against cetane number. The curves are straight lines and the slopes have the values that would be expected from a variation in cetane number. The points for the commercial marine fuel oil and for the gasoline-fuel oil mixture are farthest from the straight line. The variation of the ignition lag of the marine fuel oil is equivalent to only 1°, which is almost within the precision of the tests. The point for the gasoline-fuel oil mixture is off the curve because maximum rate of pressure rise is not necessarily a function of cetane number.

The fuel-oil dopes were expected to act as combustion accelerators; that is, the dope would not only reduce the ignition lag of a given fuel but would also cause more fuel to burn in the early part of the expansion stroke. The effectiveness of combustion would be improved by decreasing late burning and the power output should be increased for a given fuel consumption. Engine tests of the fuels containing accelerators, however, showed little if any increase in power although the ignition lags did decrease.

The results of the several combustion analyses are shown in figure 12; the curves show that the ignition lags are decreased by the fuel dopes, as was previously determined directly from the indicator cards. In spite of the different times at which ignition occurs, the variations in the total amounts of fuel burned (or the variations in effectiveness of combustion) are small during the cycle. When the curves are shifted so that they all rise from the origin, the rates of burning of the doped fuel oils are seen to be slower than those for the undoped fuel oils; that is, the rate of burning for several degrees after ignition is slower for the doped fuel oils. The fuel oil with the longest ignition lag, No. 3 furnace oil, gave the fastest rate of burning at all crank angles. For all the undoped and the doped fuel oils, the combustion continues late in the cycle and, at large loads, is conducive to a smoky exhaust.

## Gasoline as Auxiliary Fuel

It was thought that a mixture of 25 percent gasoline and 75 percent fuel oil (see table I and fig. 13) would

evaporate faster than fuel oil alone and that more of the total fuel charge would burn earlier than for undoped fuels. The fuel oil was expected to ignite first, owing to its lower ignition temperature, but the gasoline was expected to evaporate more quickly than the fuel oil and to produce better combustion during the early part of the expansion stroke. The cetane number of the mixture was 42.4, however, compared with 62.5 for the fuel oil alone and the ignition lag in the engine was increased 17-1/2 percent, possibly owing to the cooling action of the rapidly evaporating gasoline. The rate of pressure rise decreased 14 percent, the maximum cylinder pressure decreased 4 percent, and the combustion sound, unexpectedly, became very low.

The addition of 25 percent gasoline to fuel oil greatly increased the fire hazard because, as table I shows, it decreased the flash point from 236° F. to below 80° F.

The engine-performance test of the gasoline-fuel oil mixture showed that the mean effective pressure was 3 percent lower than for fuel oil alone and that the fuel consumption increased. As the heating value of the fuel mixture was the same as for a like weight of fuel oil, the effect of the gasoline must have been to cause slower rather than faster burning with a consequent decrease in power.

### Mixed Injection of Alcohol and Fuel Oil

From the indicator cards, of which figure 14 is representative, the addition of alcohol is seen to have increased the ignition lag by as much as 88 percent for the 40-percent alcohol mixture. The cause of this large increase may have been the cooling of the fuel and the air charge by evaporation of the alcohol. As usual with increased ignition lags, the rate of pressure rise (fig. 15), the maximum cylinder pressure, and the roughness increased with increased percentages of alcohol until roughness became intolerable. A mixture of 80 percent alcohol and 20 percent fuel oil could not be ignited at a compression ratio of 14.5. The spontaneous ignition temperature of fuel oil is about 500° F. and that of alcohol is about 1,025° F. (reference 11). The high ignition temperature required by alcohol and the excessive cooling of the fuel and air mixture by evaporation of the large percentage of alcohol must have been responsible for suppressing ignition.

Engine power decreased and fuel consumption increased (fig. 16) as the proportion of alcohol was increased, especially for mixtures with more than 25 percent alcohol. The heating value was 19,900 B.t.u. per pound for the fuel oil and 11,700 B.t.u. per pound for the 90 percent pure alcohol so that power comparisons are more fairly made on a basis of equal heat input. On this basis (fig. 15), the use of alcohol was more favorable; for conditions of no excess air, the power remained practically constant with variations in the percentage of alcohol. Of course, more total weight of fuel oil and alcohol is required, a factor which alone precludes the use of alcohol in compression-ignition engines for aircraft.

### Separate Injection of Alcohol and Fuel Oil

The addition of a small charge of alcohol to the fuel-oil charge considerably lowered the sound of combustion. At the start of exhaust haze, a small added charge of alcohol slightly increased the power and the exhaust became a white smoke. For the 50 percent alcohol and 50 percent fuel oil mixture by weight, the engine operation was always rough. When the alcohol was injected either 15° before the fuel oil or leading the fuel oil by 293°, as during the intake stroke, the engine operation was rough and unsteady and the fuel-oil injection advance angle became critical. Injection of the alcohol 15° after the fuel oil caused the exhaust to become a white smoke without influencing power (fig. 17).

Simultaneous injection of fuel oil from both fuel valves (fig. 2) gave lower brake mean effective pressures (fig. 17) than injection of the same fuel quantity from one fuel valve (fig. 1) doubtless because overrich regions occurred at the zones of spray interference. For the simultaneous injection of fuel oil and alcohol, a similar interference occurred and combustion was probably adversely influenced. Comparison of performance, however, is considered indicative. In the study of figure 17, it should be remembered that the air charge is sufficient to require but 0.00034 pound of fuel oil for complete combustion. At all except very large fuel quantities, the power is lower for the half-alcohol and half-fuel-oil charge because of the lower heating value of the alcohol of given charge weight.

It was believed that injection of alcohol on the in-

take stroke might increase the volumetric efficiency by cooling of the incoming-air charge. Volumetric efficiency tests showed that the air charge was slightly less, possibly because the air flow into the cylinder was obstructed by the fuel spray and possibly because the alcohol evaporated quickly from the hot chamber walls to help fill the cylinder. The very early injection of the alcohol did give more time for vaporization and mixing with the air charge and was advantageous, as evidenced by the fact that the maximum power was higher by 4 percent than for any other condition of injection.

## CONCLUSIONS

1. Fuel oils of high cetane number gave no more power than fuel oils of low cetane number but had less ignition lag, lower rates of pressure rise, and smoother engine operation over a complete load range at 2,000 r.p.m.

2. Increased engine speeds and boost pressures resulted in smoother engine operation and permitted the use of fuel oils of low cetane number.

3. Fuel dopes decreased ignition lags and rates of pressure rise and increased smoothness of engine operation. The addition of 4 percent tetranitromethane increased engine power by less than 3 percent.

4. Fuel dopes improved neither the completeness nor the effectiveness of combustion.

5. Alcohol as an auxiliary fuel, in general, decreased power as the proportion of alcohol increased. Any increases in power obtained by double injection did not exceed 4 percent and were obtained at the expense of increased fuel consumption. Alcohol increased the ignition lag, the rate of pressure rise, and the roughness of operation.

Langley Memorial Aeronautical Laboratory,
   National Advisory Committee for Aeronautics,
      Langley Field, Va., June 23, 1939.

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TABLE I - PHYSICAL AND CHEMICAL PROPERTIES OF UNDOPED AND DOPED FUEL OILS

| Fuel | Specific gravity (60/60° F.) | A.P.I. gravity (deg.) | Flash point, closed cup (°F.) | Cloud point (°F.) | Pour point (°F.) | Saybolt Universal Viscosity (sec.) | | Total sulfur (percent) | Heat value, calorimeter gross (B.t.u. per lb.) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | At 32°F. | At 100°F. | | |
| 1: Laboratory | 0.833 | 38.37 | 236 | 26 | 25 | 93 | 44 | 0.04 | 19,909 |
| 2: Navy M-306 (aircraft standard) | .824 | 40.22 | 166 | - | -20 | - | 33 | .11 | 19,790 |
| 3: Commercial marine | .843 | 36.35 | 182 | 14 | 15 | 61 | 38 | .30 | 19,578 |
| 4: Navy 7-0-20 (submarine standard) | .852 | 34.58 | 188 | 12 | 10 | 65 | 39 | .26 | 19,660 |
| 5: No. 3 furnace oil | .877 | 29.85 | 162 | Indistinct | -65 | 58 | 38 | .18 | 19,315 |
| 6: No. 3 furnace oil + 1 percent ethyl nitrate | .875 | 30.21 | 125 | -10 | -25 | 57 | 38 | .20 | 19,257 |
| 7: Laboratory + 2.5 percent iso-amyl nitrate | .834 | 38.16 | 145 | 26 | 25 | 86 | 43 | .10 | 19,696 |
| 8: Laboratory + 4 percent tetra-nitromethane | - | - | - | - | - | - | - | - | - |
| 9: Laboratory + 25 percent 87 octane gasoline | .799 | 45.60 | Below 80 | 6 | 10 | 42 | 35 | .12 | 19,775 |
| 10: Laboratory + 10, 25, and 40 percent alcohol | - | - | - | - | - | - | - | - | - |

| | Spontaneous ignition temperature (°F.) | Aniline point (°F.) | Diesel index number | Cetane number | Distillation characteristics | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | First drop (°F.) | 10 cc. (°F.) | 50 cc. (°F.) | 90 cc. (°F.) | End point (°F.) | Recovered (percent) |
| 1: Laboratory | - | 186.3 | 71.5 | 62.5 | 529 | 546 | 575 | 622 | 672 | 98.4 |
| 2: Navy M-306 (aircraft standard) | - | 154.0 | 61.7 | 59.9 | 384 | 414 | 466 | 551 | 597 | 98.0 |
| 3: Commercial marine | 490 | 160.9 | 58.5 | 58.0 | 408 | 453 | 525 | 619 | 673 | 98.4 |
| 4: Navy 7-020 (submarine standard) | 495 | 156.7 | 54.2 | 49.2 | 421 | 475 | 533 | 600 | 661 | 98.7 |
| 5: No. 3 furnace oil | 575 | 126.2 | 37.7 | 29.9 | 375 | 438 | 497 | 581 | 640 | 98.7 |
| 6: No. 3 furnace oil - 1 percent ethyl nitrate | 495 | 130.4 | 39.4 | 47.7 | 212 | 442 | 504 | 590 | 647 | 98.3 |
| 7: Laboratory + 2.5 percent iso-amyl nitrate | 485 | 183.2 | 69.9 | 88.1 | 188 | 545 | 575 | 622 | 660 | 98.0 |
| 8: Laboratory + 4 percent tetra-nitromethane | - | - | - | - | - | - | - | - | - | - |
| 9: Laboratory + 25 percent 87 octane gasoline | 730 | 170.8 | 77.9 | 42.4 | 135 | 182 | 560 | 617 | 658 | 97.8 |
| 10: Laboratory + 10, 25, and 40 percent alcohol | - | - | - | - | - | - | - | - | - | - |

(Side)                    (End)

Figure 1 - Fuel-spray axes and combustion chamber

Relative fuel-spray lengths at T.C. for an i.a.a.
of 10° B.T.C.; orifice diameters indicated.

Fig.1

TABLE II – IGNITION AND COMBUSTION PERFORMANCE OF UNDOPED AND DOPED FUELS

| Fuel | Octane number | Fig- ure | Injec- tion advance angle (crank deg.) | Ignition lag | | Maximum cylinder pressure (lb./sq. in.) | | Maximum rate of pressure rise | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | (deg.) | (sec.) | Trapped | Balanced | (lb./sq. in./deg.) | (lb./sq.in./sec.) |
| 1: Laboratory | 62.5 | 3 | 12.0 | 8.5 | 0.00071 | 890 | 920 | 43 | 520,000 |
| 2: Navy M-306 (aircraft standard) | 59.9 | - | 12.0 | 9.0 | .00075 | 890 | 935 | 51 | 612,000 |
| 3: Commercial marine | 56.0 | - | 12.0 | 8.0 | .00067 | 900 | 930 | 40 | 480,000 |
| 4: Navy 7-O-20 (submarine standard) | 49.2 | - | 12.0 | 9.5 | .00079 | 875 | 930 | 50 | 600,000 |
| 5: No. 3 fur- nace oil | 29.9 | 4 | 12.0 | 12.5 | .00104 | 870 | 1,050 | 70 | 840,000 |
| 6: No. 3 fur- nace oil + 1 percent ethyl nitrate | 47.7 | 7 | 12.0 | 10.0 | .00083 | 900 | 960 | 54 | 650,000 |
| 7: Laboratory + 2.5 per- cent iso- amyl nitrate | 66.1 | 8 | 12.0 | 6.5 | .00054 | 910 | 950 | 23 | 276,000 |
| 8: Laboratory +4 percent tetranitro- methane | - | 9 | 12.0 | 6.5 | .00054 | 950 | 950 | 28 | 336,000 |
| 9: Laboratory + 25 per- cent 87 octane gasoline | 42.4 | 11 | 12.0 | 10.0 | .00083 | 815 | 875 | 37 | 444,000 |
| 10. Laboratory + 40 percent alcohol | - | 14 | 12.0 | 18.0 | .00133 | 875 | 1,000 | 97 | 1,165,000 |
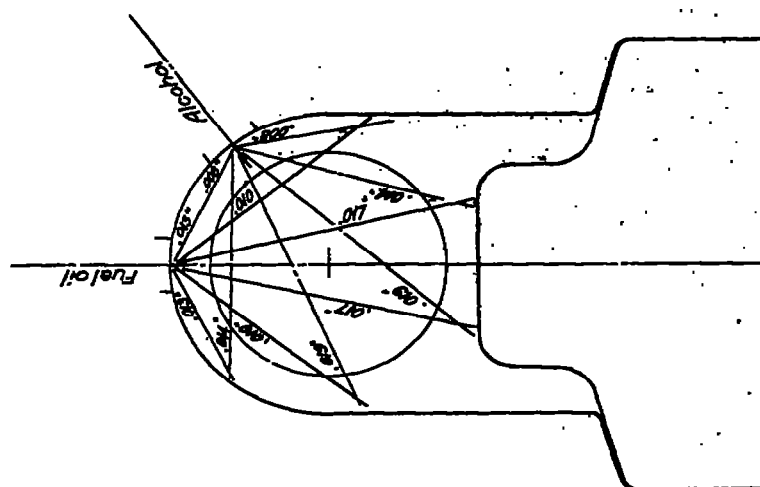


Figure 2.- Fuel-spray arrangement for separate injection of fuel oil and alcohol. Angles between adjacent sprays 25° for both nozzles. Orifice diameters indicated

Fig. 3
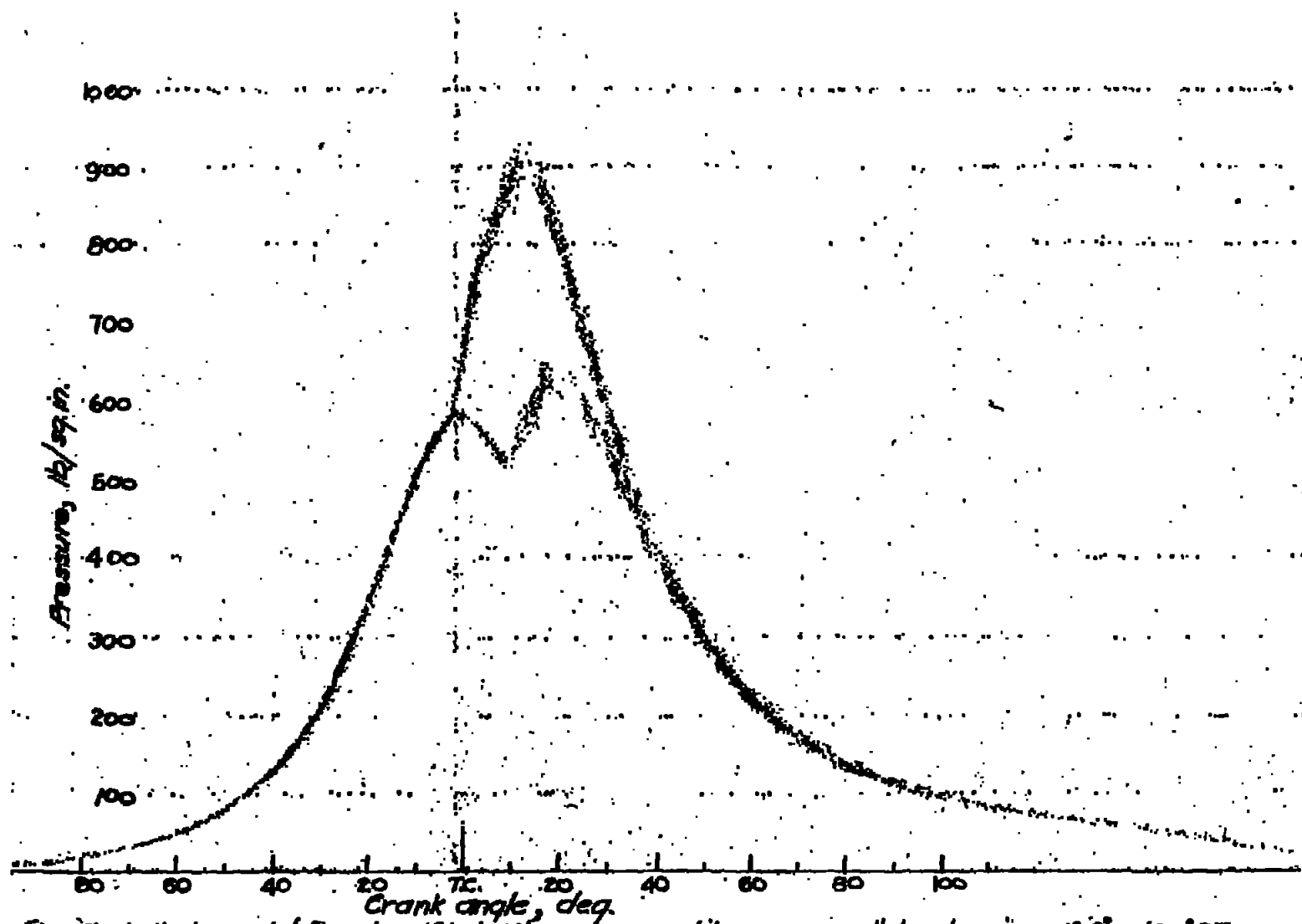


Figure 3.- Indicator card, laboratory fuel oil; quantity, 0.000389 lb/cycle; i.a.a., 12.0° and 2.5° B.T.C.; ignition lag, 8.5°; maximum rate of pressure rise, 43 lb/sq.in./deg.
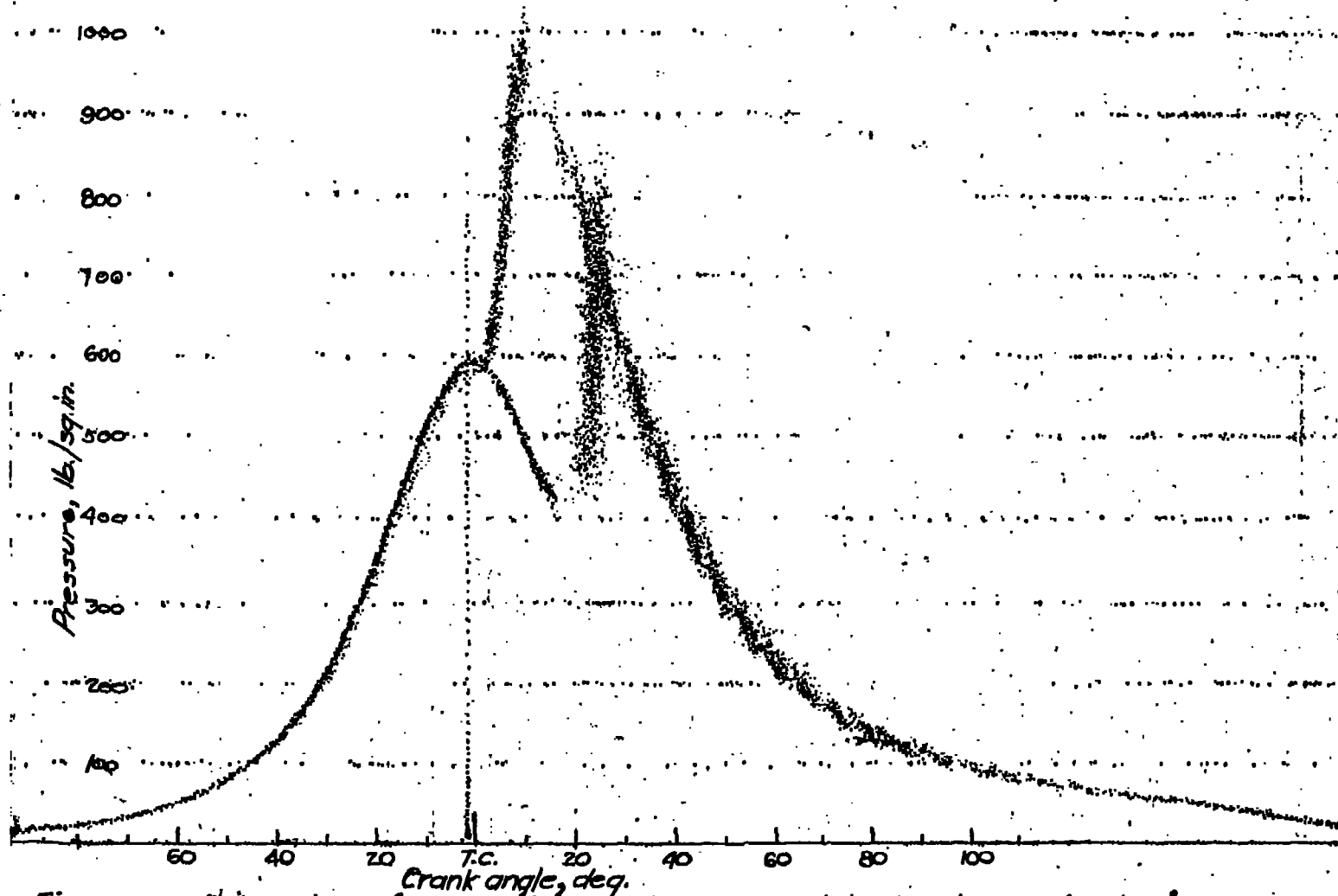
Figure 4. – Indicator card, No. 3, furnace oil; quantity, 0.000366 lb./cycle; l.a.a. 12.0° and 2.5°; ignition lag, 11.5°; maximum rate of pressure rise, 70 lb./sq. in./deg.

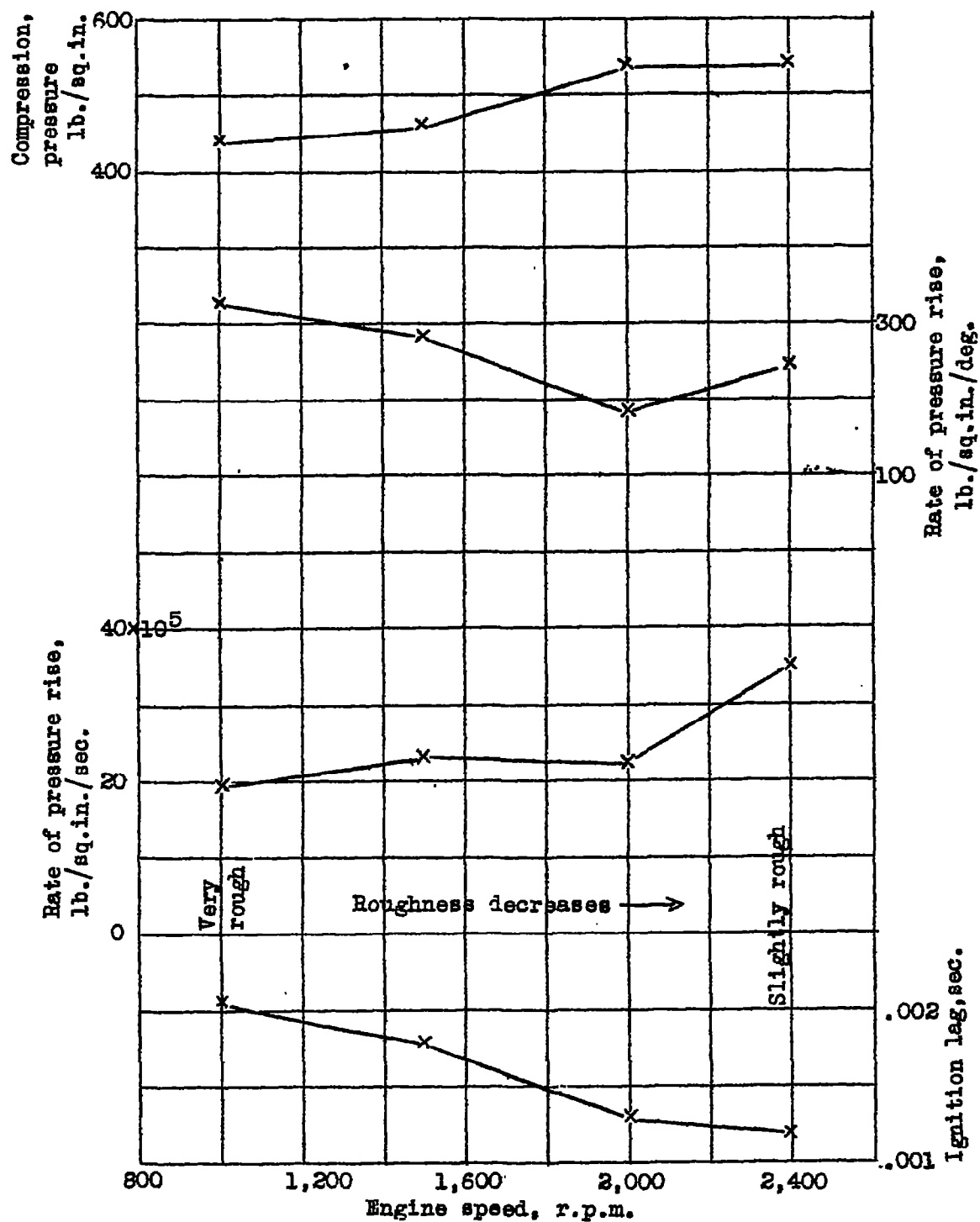Fig. 4

Figure 5.- Effect of engine speed on combustion characteristics.
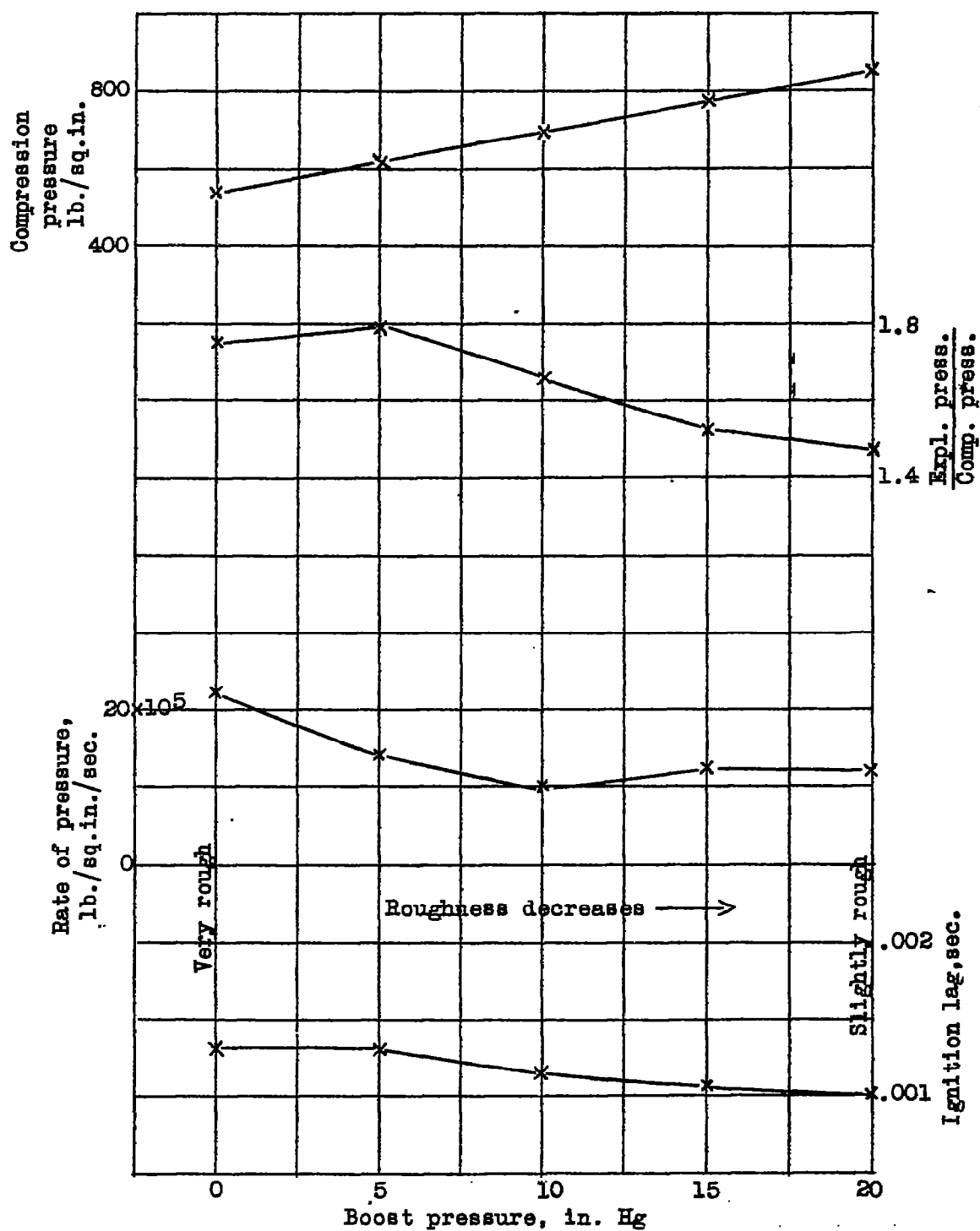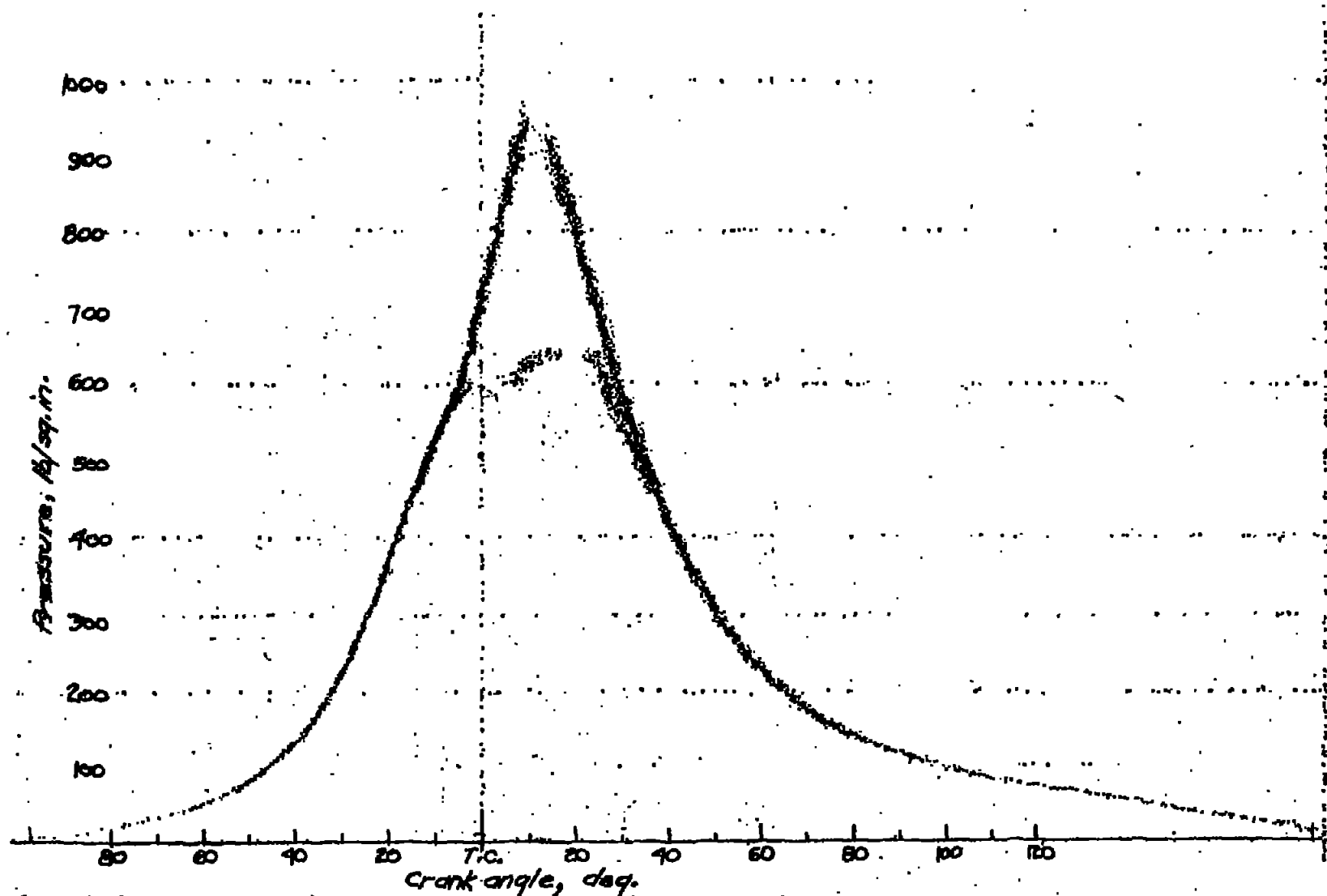5-by 6-inch test engine; No.3 furnace oil.

Figure 6.- Effect of boost pressure on combustion characteristics.
5-by 6-inch test engine; engine speed, 2,000 r.p.m.;
i.a.a., 12°; No.3 furnace oil; air-fuel ratio, 14.5.

FIG. 7
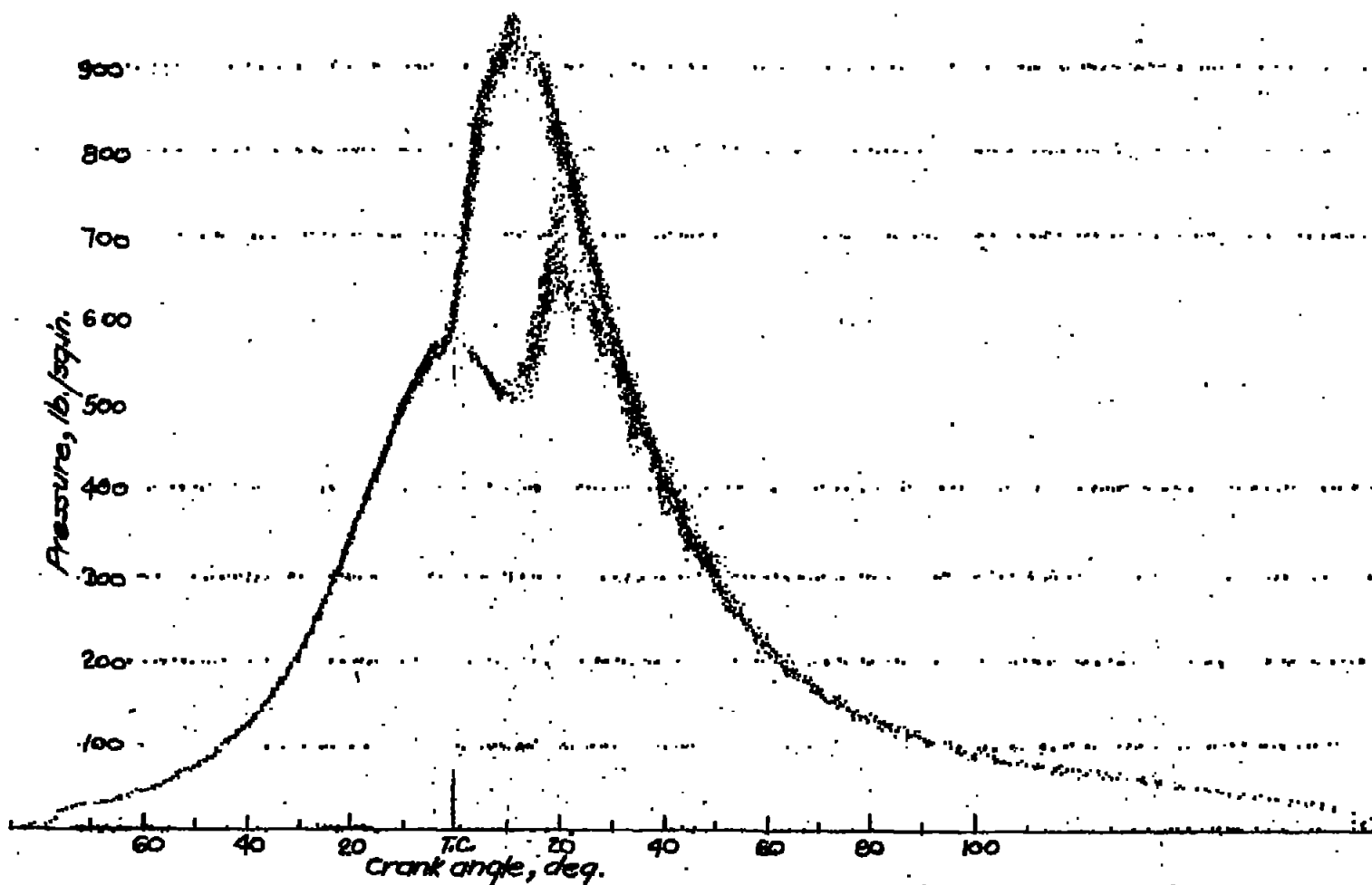


Figure 7.- Indicator card, No.3 furnace oil + 1 percent ethyl nitrate; quantity, 0.00037 lb./cycle; lag., 12.0° and 2.5°; ignition lag, 10°; maximum rate of pressure rise, 54 lb/sq.in./deg.
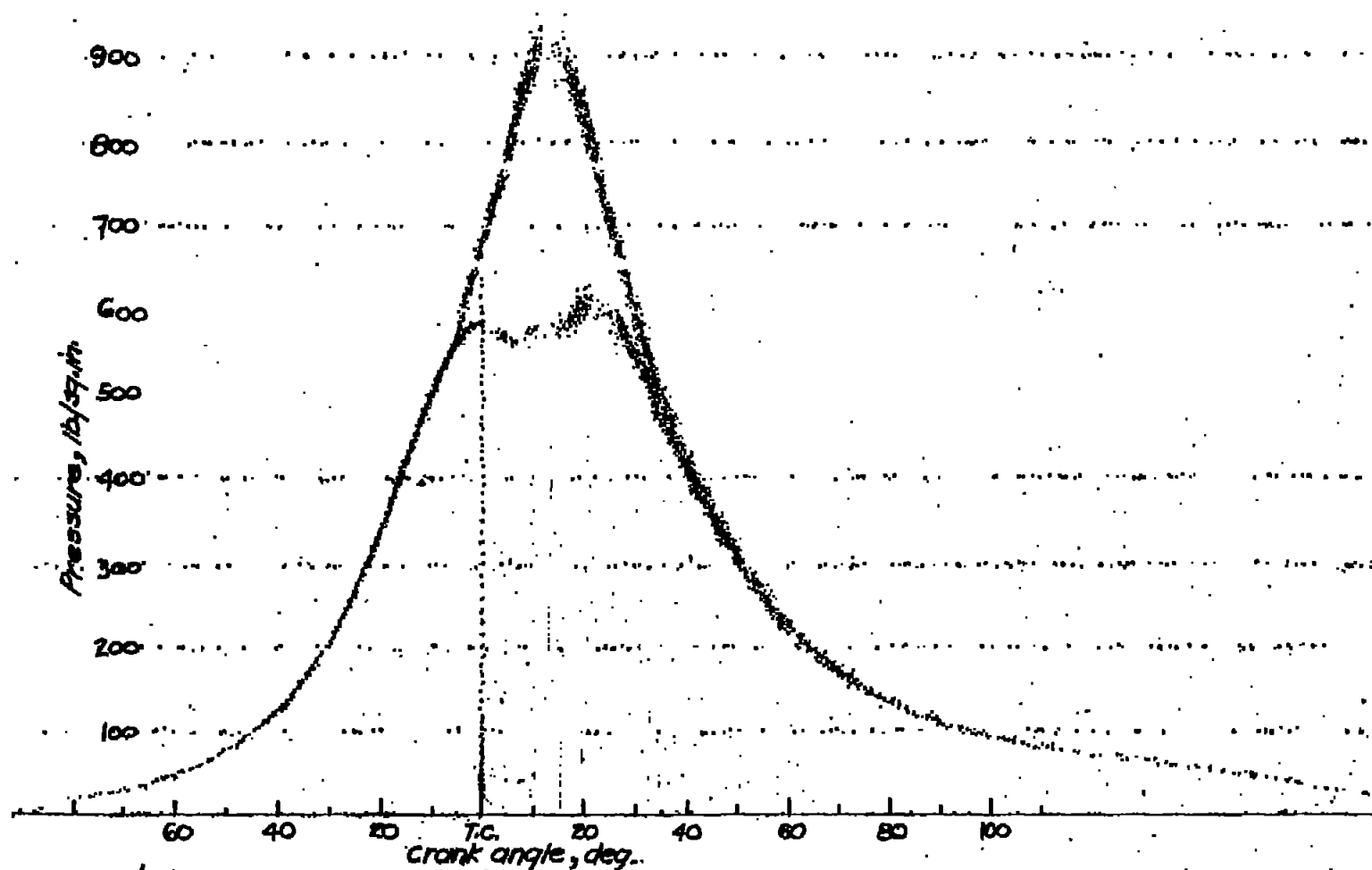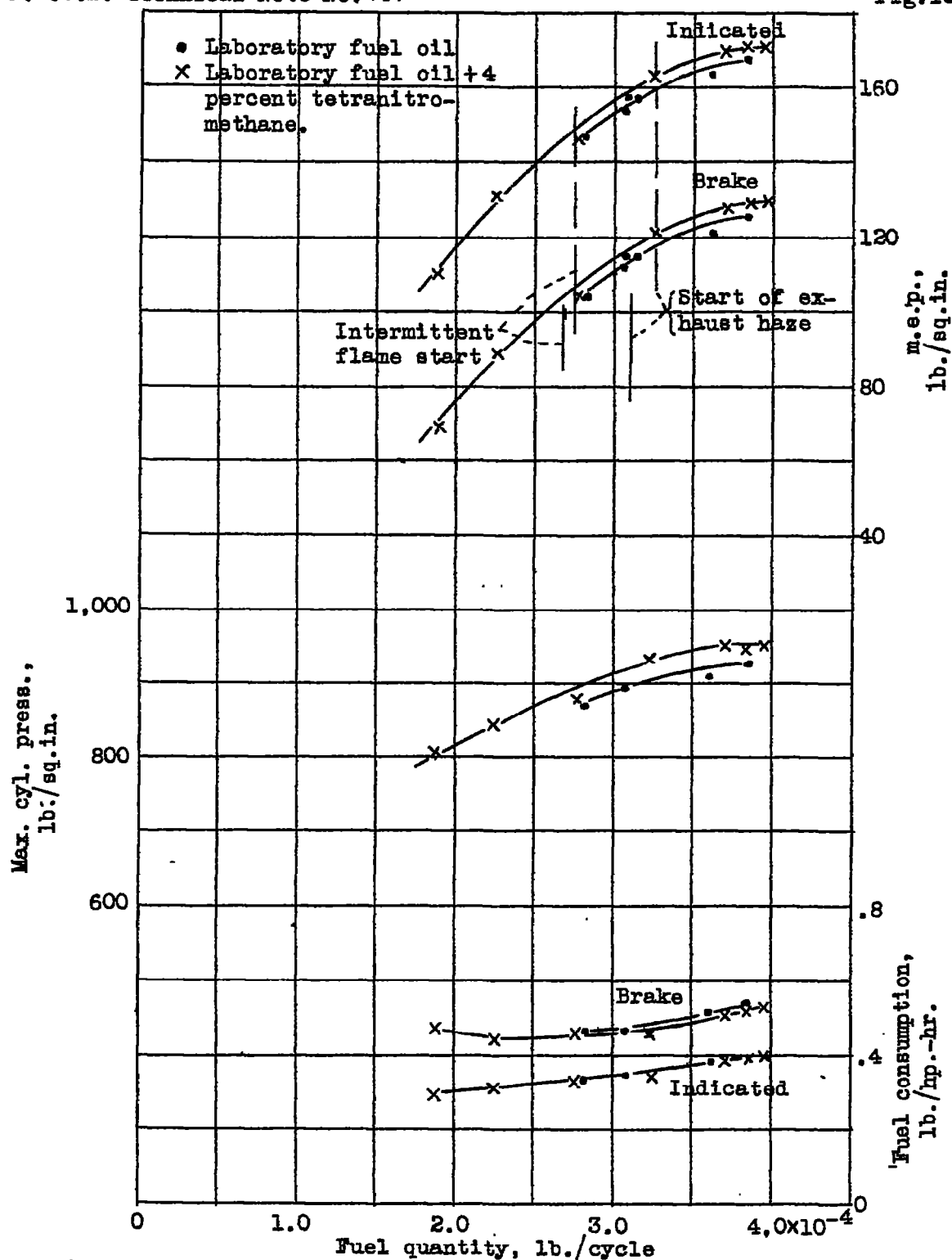
Figure 8.- Indicator card, laboratory fuel oil + 2.5 percent iso-amyl nitrate; quantity, 0.000376 lb/cycle; i.a.g., 12.0 and 2.5°; ignition lag, 6.5°; maximum rate of pressure rise, 23 lb./sq.in./deg.

Fig. 8

Pressure, lb/sq.in.

1000

900

800

700

600

500

400

300

200

100

80   60   40   20   T.C.   20   40   60   80   100   120

Crank angle, deg.

Figure 3—Indicator card, laboratory fuel oil + 4 percent tetranitromethane; quantity, 0.00038 lb/cycle; i.a.a., 12.0° and 4.5°; ignition lag, 6.5°; maximum rate of pressure rise, 28 lb/sq.in./deg.

Fig. 9

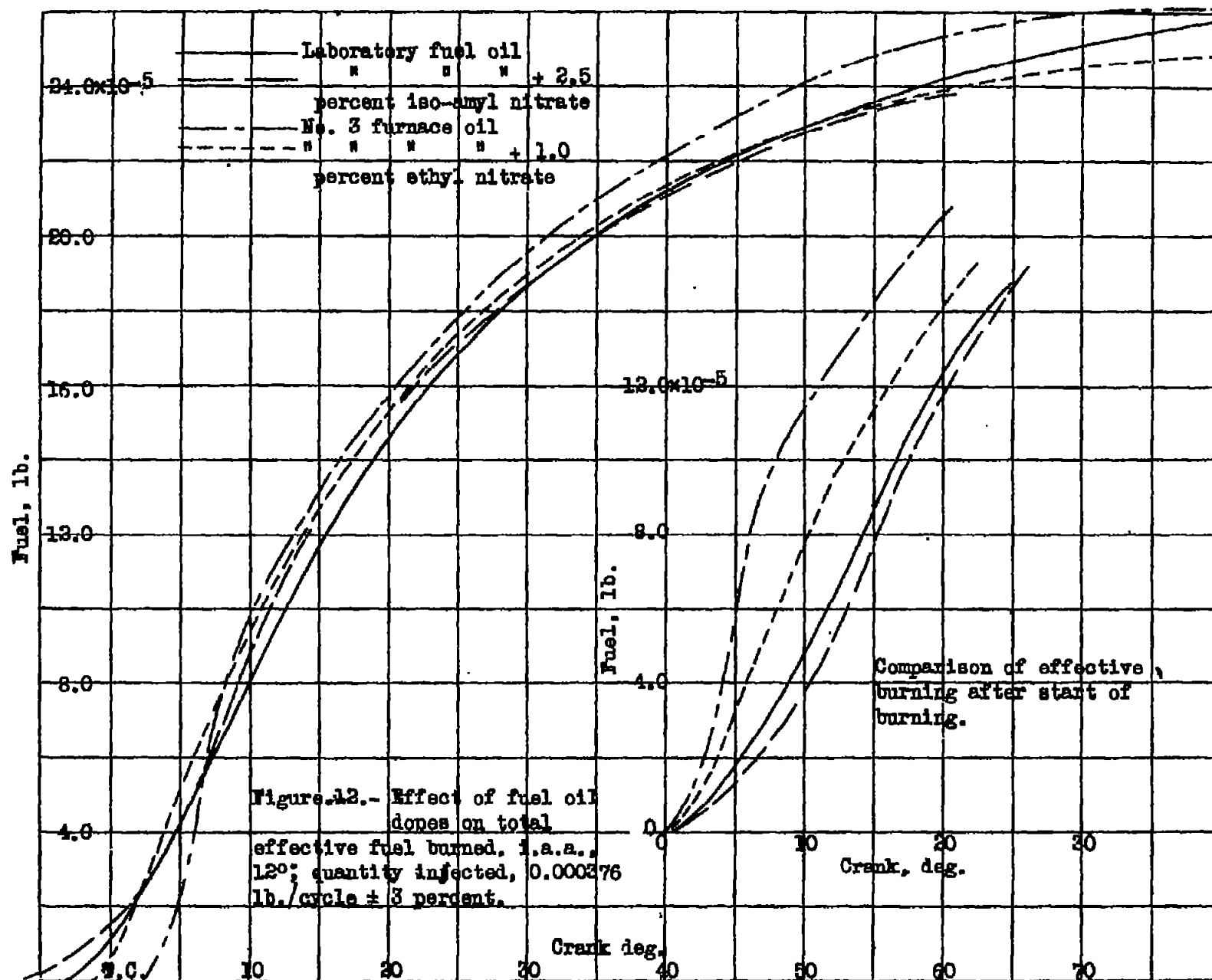Figure 10.- Effect of tetranitromethane on engine performance. Constant i.a.a., 12⁰.
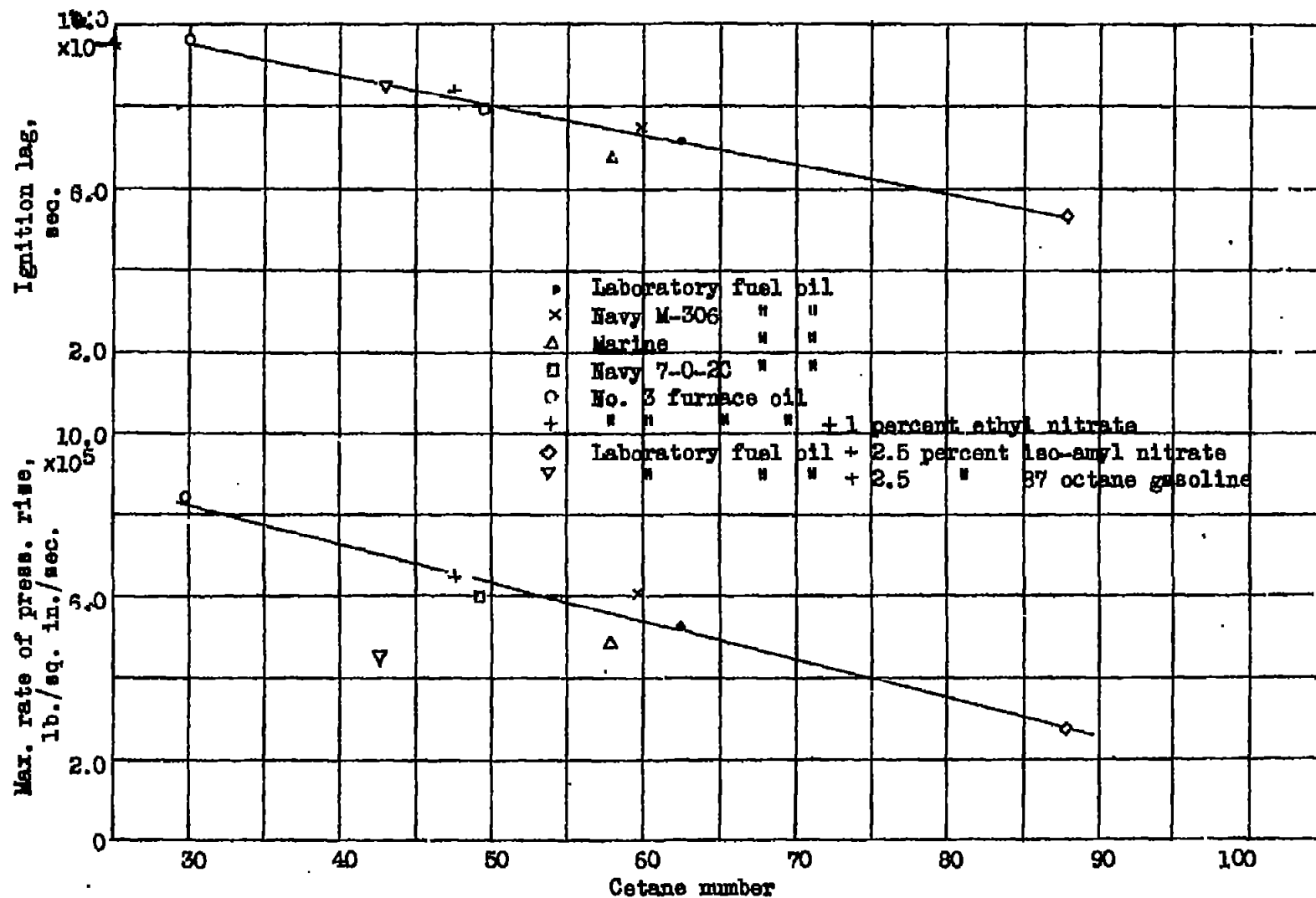
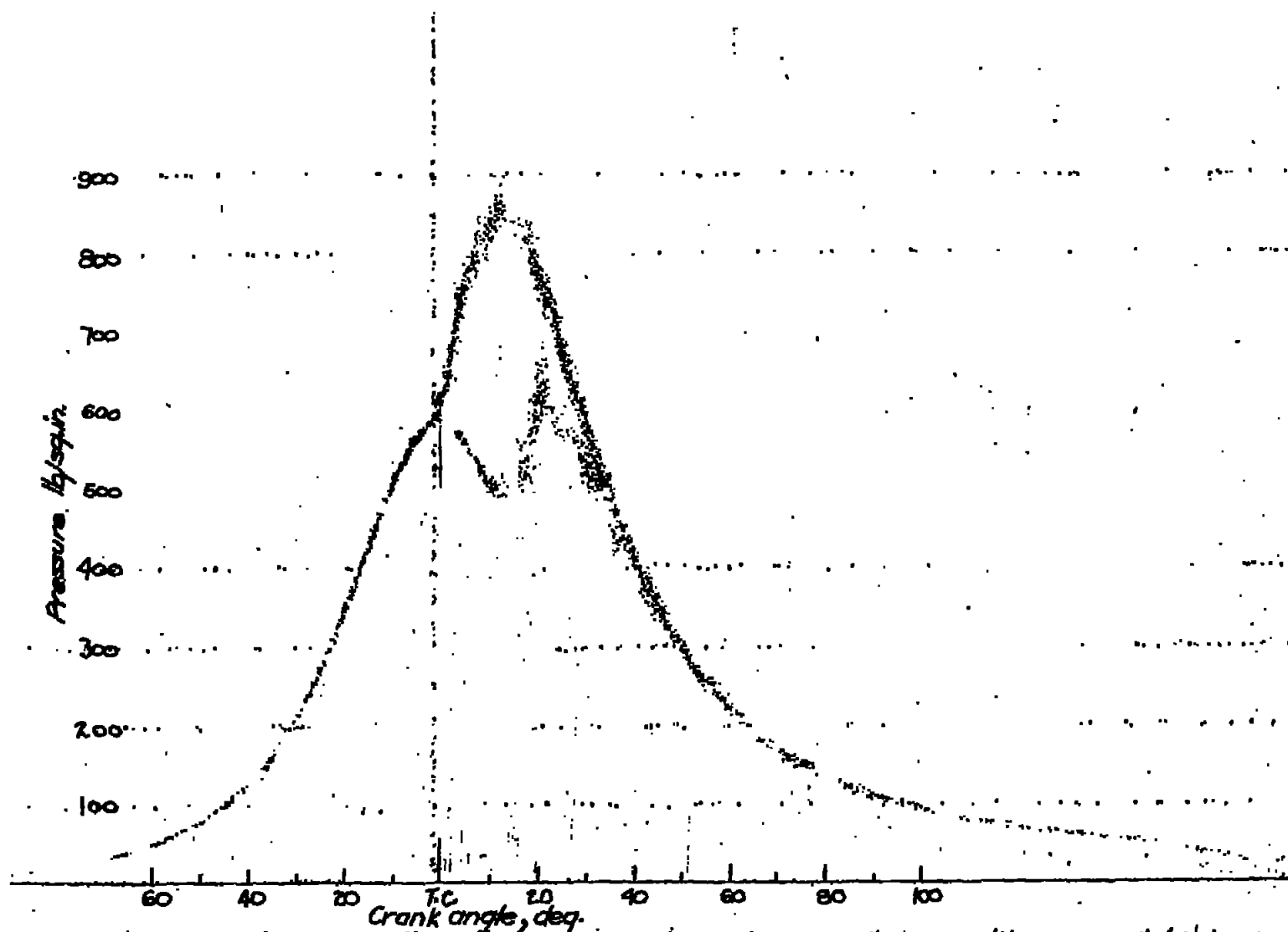Figure 11.- Cetane number from C.F.R. engine against indicator-card data from high-speed test engine.

Fig. 11

Laboratory fuel oil
"      "    "   + 2.5 percent iso-amyl nitrate
No. 3 furnace oil
"   "    "    "   + 1.0 percent ethyl nitrate

Comparison of effective burning after start of burning.

Figure 12.- Effect of fuel oil dopes on total effective fuel burned. i.a.a., 12°; quantity injected, 0.000376 lb./cycle ± 3 percent.

Fuel, lb.

Crank deg.

Crank, deg.

Fig. 12

Figure 13.—Indicator card, laboratory fuel oil + 25 percent 87 octane gasoline; quantity, 0.000373 lb/cycle; i.a.a., 12.0° and 2.5°; ignition lag, 10°; maximum rate of pressure rise, 57 lb/sq.in./deg.

Fig. 13

Fig. 14
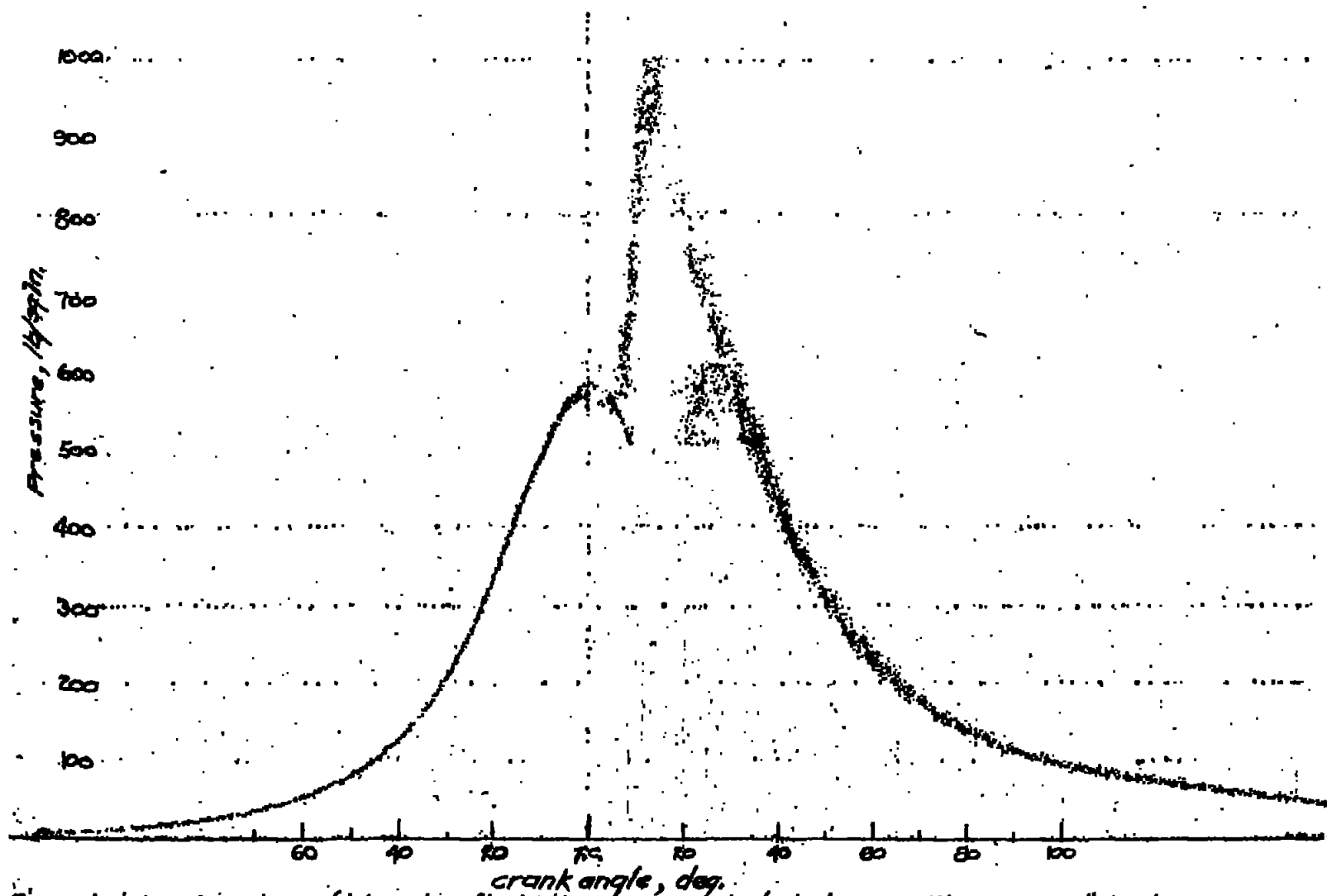


Figure 14.- Indicator card, mixture of laboratory fuel oil + 40 percent alcohol; quantity, 0.000365 lb/cycle, l.o.a., 12° and 4°; ignition lag, 16°; maximum rate of pressure rise, 97 lb./sq.in./deg.
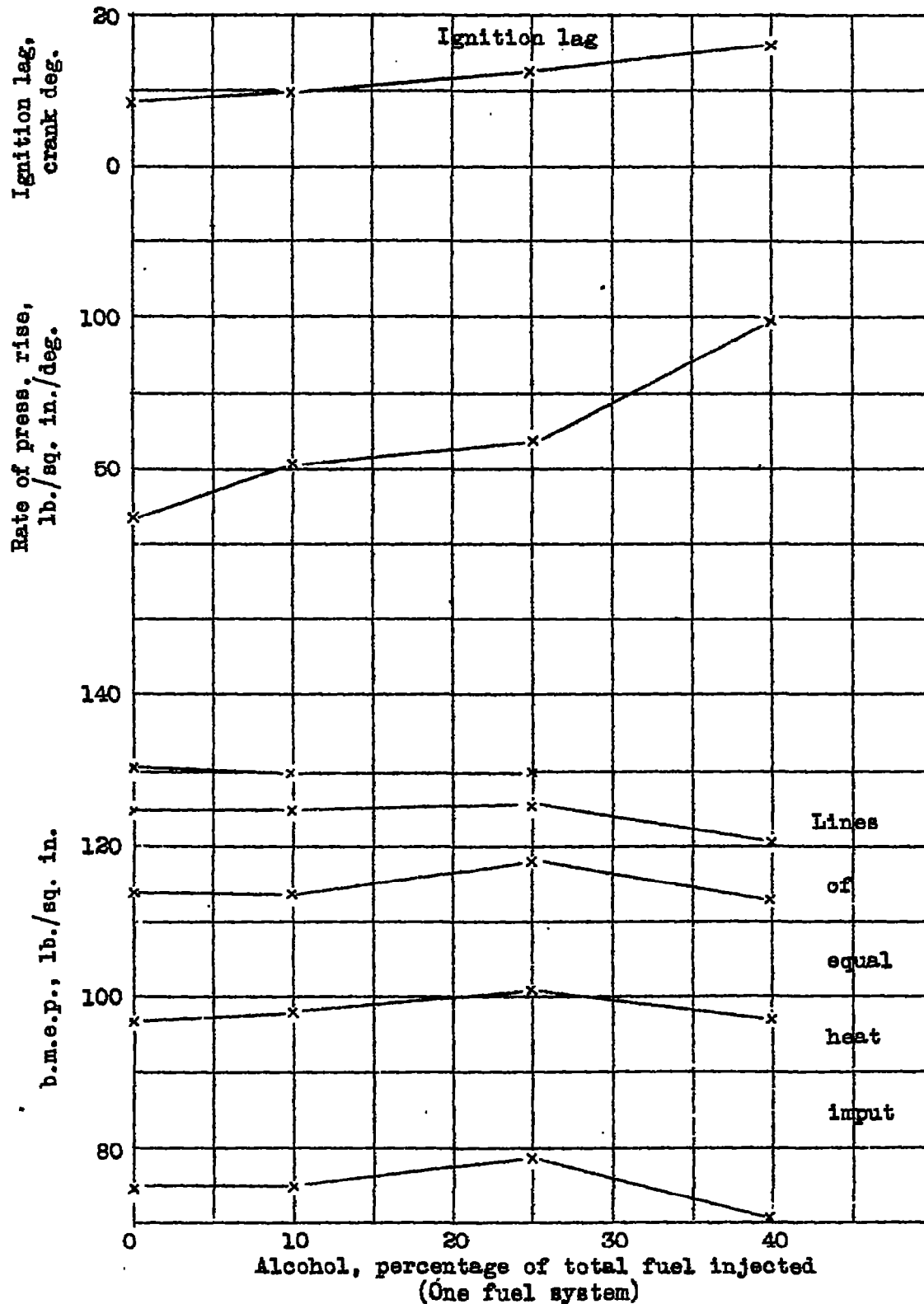
Figure 15.- Effect of alcohol-fuel oil mixtures on several
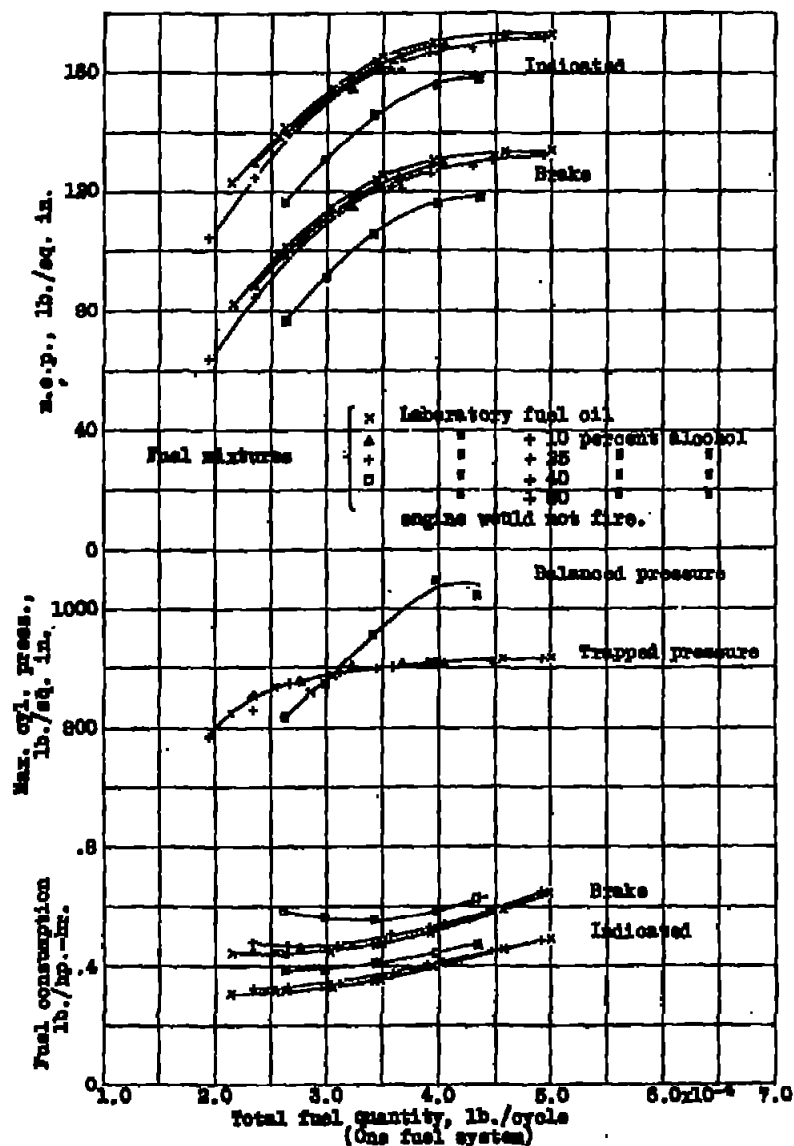engine performance factors.

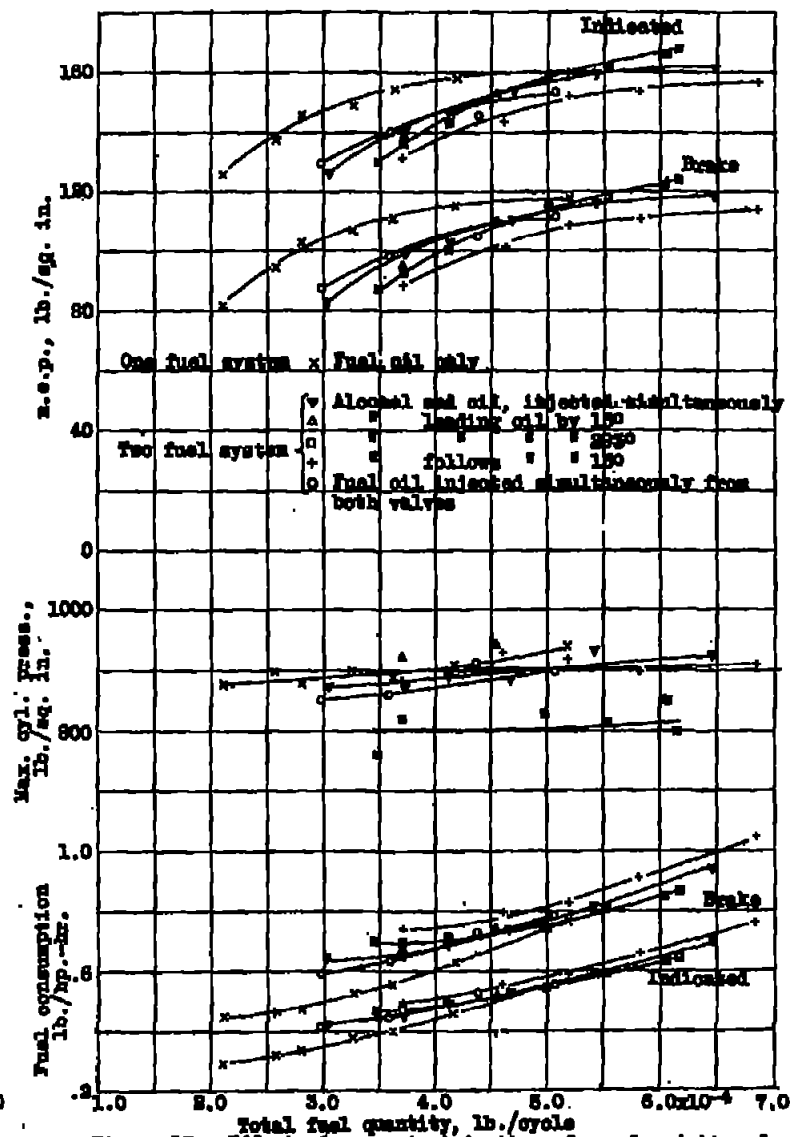Figure 16.- Effect of alcohol-fuel oil mixtures on engine performance.

Figure 17.- Effect of separate injection of equal weights of fuel oil and alcohol on engine performance.